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S. C. Sundstrom

C. G. Blood

S. A. Matheny

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NAVAL HEALTH RESEARCH CENTER
P. O. BOX 85122
SAN DIEGO, CALIFORNIA 92186 – 5122

NAVAL MEDICAL RESEARCH AND DEVELOPMENT COMMAND
BETHESDA, MARYLAND

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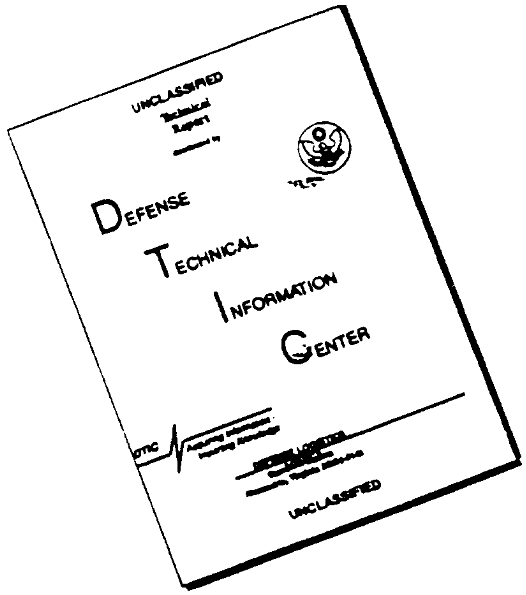

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A Linear Programming Model

Scott C. Sundstrom *
Christopher G. Blood
Serge A. Matheny *

Medical Information Systems and Operations Research Department
Naval Health Research Center
P.O. Box 85122
San Diego, CA 92186-5122

* GEO-CENTERS, INC.

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SUMMARY

Through the use of linear programming techniques, the optimal number and positioning of patient evacuation assets within a theater of operations may be determined to ensure the orderly transport of casualties from the front lines to third echelon medical treatment facilities. The Probabilistic Location Set Covering Problem has been chosen as the core module for a linear programming model to assist in these determinations. The Optimal Placement of Casualty Evacuation Assets (OPTEVAC) model prompts the user to enter the dimensions of the theater, troop deployment nodes, types of evacuation assets available, and preferred locations of medical treatment facilities. The OPTEVAC model then provides output as to the required numbers of ground and air ambulances as well as the optimal positioning of those evacuation assets and ambulance exchange points.

The Optimal Placement of Casualty Evacuation Assets: A Linear Programming Model

Combat casualties in a theater of operations are treated at mobile medical facilities organized into a series of echelons with the facilites at the forward echelons having the greatest mobility but least surgical capability[1]. The efficient evacuation of casualties from echelon to echelon is essential to ensure the wounded personnel reach a facility with the capability to render the required level of care. Distances between medical treatment facilities, as well as factors such as the type of terrain and mode of transportation, may all impact the evacuation process. Likewise, the number of treatment facilities deployed and where they are located greatly affects the casualty handling process and the ability to provide adequate casualty care.

In the Kuwaiti theater of operations, treatment facilities were spaced further apart than the distances considered under the existing medical evacuation doctrine; consequently, some casualties requiring evacuation were out of helicopter range or in locations not accessible to fixed-wing aircraft[2]. While casualties were relatively few in the Gulf Conflict, and the wounded personnel did receive needed treatment in a timely fashion, future operations may yield larger numbers of casualties with a greater potential for overwhelming the casualty evacuation system. Accurate assessments of the required numbers, types, and deployment locations of the evacuation assets ensure that wounded personnel are transported expeditiously from the point of injury through the various echelons of care to an Echelon III treatment facility, as dictated by the severity of the wound.

The focus of this report is the selection and development of an appropriate linear programming technique which will allow optimization of the number and positioning of evacuation assets at given treatment facilities in a theater of operations. Because inter-theater evacuation of patients is handled for all services by the U.S. Transportation Command (TRANSCOM), the present effort focuses on intra-theater casualty evacuation -- transporting wounded Marines from the point of injury, through Echelons I and II in the combat zone, and ending at an Echelon III level of care

(e.g., Fleet Hospital). The methodology developed will be flexible enough to allow incorporation of treatment facilities and evacuation assets of other service branches within the combat zone, particularly those of the Army which may very well have forces interdeployed with the Marines.

The optimization planning tool will incorporate the projection methodology of the FORECAS system[3] which simulates daily casualty averages and maximum daily patient loads. The simulations generated by FORECAS are based on the statistical properties of empirical data observed from four previous ground combat operations[4]. In addition to patient flows, the optimization model will require data on troop strengths and deployment locations, terrain, size of theater, numbers and types of ground/air ambulances available, types and locations of Echelon II and Echelon III treatment facilities, and length of evacuation delay. Using this input, the planning tool will compute the optimum numbers, types, and deployment coordinates of the evacuation assets, including ambulance exchange points.

A comprehensive examination of existing optimization models was conducted and the Probabilistic Location Set Covering Problem (PLSCP)[5,6] was determined to be the one that most accurately represented the demands and constraints needed to model the intra-theater evacuation of casualties. Other optimization models that were examined include the location set covering problem (LSCP), the maximal covering location problem (MCLP), the maximum availability location problem (MALP), and two derivatives of the chosen PLSCP: the α-reliable p-center problem and the maximum reliability location problem (MRLP). The PLSCP was chosen over the other models because it minimizes the total number of required evacuation assets within the theater, while at the same time incorporating randomness in vehicle availability. The vehicles of the other models investigated, are sited only on the basis of geographical coverage and not on the basis of availability. The assumption underlying these alternative models is that the vehicles are continuously available for evacuation of casualties. In low demand operations, this assumption is not unreasonable; however in high tempo military operations where frequent casualty calls keep evacuation assets on the roads, this assumption cannot be justified. Use of the PLSCP algorithms within the evacuation model (OPTEVAC) will allow medical planners to input the "alpha-level" at which the optimization model

is to run -- a statistic which represents the percentage of the maximum daily casualty load for which the proposed assets will meet the demand. The maximum daily casualty load will be computed by adding the maximum projected wounded-in-action (WIA) incidence to the maximum projected disease and non-battle injury (DNBI) incidence during the operation. The alpha level is important because of the casualty "spikes" that occur during a combat operation. For instance, the planner may want to economize resources by deploying dedicated assets to ensure evacuation coverage for 80% of the maximum casualty load ($\alpha = .80$) and rely on "vehicles of opportunity" to transport the casualties that exceed the capabilities of these dedicated assets. Alternatively, if evacuation assets were programmed for the maximal projected daily casualty load, many assets would be used but a small percentage of the time, if at all.

Patient flows within the OPTEVAC model will be determined from the user-specified input of troop placement, with projections based on casualty distribution trends evidenced during previous combat operations. The patient stream is actually composed of two separate medical admission flows: WIA and DNBI. The daily WIA flow is generated by drawing a random deviate from an exponential distribution based on 'battle intensity'-specific averages and geographical theater considerations. Projected DNBI incidence is similarly derived using variates drawn from a lognormal distribution. The casualty generator also incorporates two other statistical patterns observed within the empirical data: cross-correlation betwen WIA and DNBI and autocorrelation within the WIA flows[2,7].

The following section describes the linear programming model (PLSCP) chosen for optimizing casualty evacuation assets and provides a detailed analysis of how the problem is mathematically represented. Essential to accurate assessment of the numbers of evacuation assets required are variables relating to the specific types of assets (transportation mode, litter capacity, range, mobility, etc.) as well as factors related to terrain and weather. The scope of the present report, however, is the linear program to be used in optimizing evacuation assets; the parameters relating to environmental conditions and ambulance characteristics are the subject of a parallel effort.

THE MODEL

The OPTEVAC model will provide medical planners with the required number and optimal placements of evacuation assets to ensure sufficient casualty transport while minimizing oversupply of ground and air ambulances. The Probabilistic Location Set Covering Problem (PLSCP) linear program has been selected as the core module for OPTEVAC, and it has been modified to make it applicable to the optimization of casualty evacuation assets in a combat theater.

The PLSCP module, incorporated into the casualty evacuation application, seeks the positions of z evacuation assets in a theater of operations which minimizes the number of vehicles (ground and air ambulances) required so that there is a 95% certainty that the user-specified evacuation demands will be met. Mathematical formulation of the PLSCP for the casualty handling process is:

minimize $z = \sum_{j \in J} x_j$

subject to

$$\sum_{j \in N_i} x_j \geq b_i \quad \forall i,$$

x_j are integers,
where b_i is the smallest integer satisfying

$$1 - \left(\frac{F_i}{b_i}\right)^{b_i} \geq .95.$$

Define

$$F_i = \left(\frac{1}{24}\right) t \sum_{k \in M_i} f_k$$

where

t = the average duration (hours) of a casualty call within the theater (average distance from a demand node to a treatment facility / weighted average speed of available assets, using the ratios of available assets);

f_k = frequency of casualty calls, or trips, at demand node k (casualty calls/day);

M_i = the set of demand nodes within S of demand node i.

Variables:

z = the total number of evacuation assets distributed over all of the facilities in the theater of operations ($\sum b_i$);

i, I = index and set of demand nodes;

j, J = index and set of treatment facility sites;

d_{ji} = the distance from facility site j to demand node i;

S = the distance standard within which a treatment facility is desired to be found;

N_i = $\{j | d_{ji} \leq S\}$; the set of facility sites within S of demand node i;

x_j = the number of evacuation assets at facility site j;

b_i = the minimum number of evacuation assets required within M_i.

The OPTEVAC planning tool consists of input screens which employ graphical user interfaces prompting the user for the information needed for the simulations. The first input that the planner must supply into the OPTEVAC model is the dimensions of the theater. An image of a grid with the user-specified dimensions will then be displayed on the computer screen immediately following this input. The next required input pertains to location of troop deployment. Following troop deployment input, the user will be asked to specify the numbers and types of medical treatment facilities and to indicate their locations within the theater. Other key inputs to the model will include factors such as battle intensity, geographical region, expected length of the operation, evacuation delay, "alpha-level" associated with the maximum projected daily casualty load, and types of evacuation assets available.

The standard PLSCP linear program, by itself, is not sufficiently robust to handle the demands of the OPTEVAC model, so modifications were required to fit it to the casualty evacuation model. The PLSCP was originally written to satisfy the demands of a city population in need of ground ambulances in a timely fashion. The urban transport problem assumed only one type of ambulance, which implied one speed and one litter capacity. In a military theater, however, there is a multitude

of vehicles available, and each has it's own distinct speed, range, and litter capacity. Furthermore, within a combat theater, different types of vehicles need to be dispatched simultaneously.

To integrate more than one type of evacuation asset into the model, information regarding the capacities, speeds, and the numbers of each vehicle available for deployment must be included. Both ground and air ambulances are actively involved in the casualty evacuation process, so a revised algorithm is needed to determine the demand, or frequency of calls per day, of a given configuration of transportation assets. This algorithm, which represents the core of the OPTEVAC model, considers the placement and allocation of evacuation assets for varying litter capacities.

The model performs the necessary distance calculations between the troop deployment nodes and the medical treatment facilites and begins to place the various types of available vehicles at treatment facilites to solve for the optimal vehicle configuration. Different placements of troop nodes and treatment facilites will of course yield different numbers and combinations of each vehicle located at the facilities. Not always will all of the available vehicles be required for a given treatment facility configuration since the model finds the minimum number of required vehicles to handle the casualty flow. Similarly, the results may indicate that more vehicles must be made available than were originally entered to handle the casualty load.

The OPTEVAC program utilizes the PLSCP module to solve for the optimal number of evacuation assets given a specific configuration of treatment facilities. As part of the PLSCP model, the first task is to determine each of the b_i variables (minimum number of required assets within demand area), and there will be as many b_i variables as there are demand nodes. Each b_i can be solved after the planner has entered the aforementioned required inputs into the program, and solving for each b_i will be accomplished by using Newton's Method[8]. Newton's Method will be used to find the b_i's after the user has entered the inputs required to solve for F_i (total evacuation asset demand). The required b_i's will be inserted into the constraint matrix of the PLSCP and hence complete the system of equations. There will be "i" (# of demand nodes) equations and "j" (# of treatment facilities) variables in the constraint matrix.

The following casualty evacuation problem, solved by the Simplex Method[9], demonstrates that OPTEVAC can yield solutions for multiple casualty evacuation asset types. In this facile example, consider a 60-day operation in which there are five Echelon II facilities, three troop deployment nodes with strengths seen in Figure 1, and that the average WIA and DNBI rates are 5.77 per 1000 strength per day and 4.22 per 1000 strength per day, respectively. Also assume that 10 ground ambulances and 2 air ambulances are available for deployment. The first calculation performed is to determine the frequency of calls per day at each troop deployment node within the theater. The necessary algorithm must factor in the placement and allocation of evacuation assets for varying litter capacities. Therefore, the PLSCP algorithm needs to be modified such that separate frequencies ($f_{k,ground}$ and $f_{k,air}$) and separate demand areas' vehicles ($b_{i,ground}$ and $b_{i,air}$) are computed for each type of vehicle. Defined below is an application of the algorithm that calculates the frequency of calls per day, when multiple vehicle assets are being used for evacuation (vehicle specifications are also listed). For instance, with only two types of vehicles (e.g., a single ground ambulance type and a single air ambulance type) this algorithm computes $f_{k,ground}$ and $f_{k,air}$ as follows:

	Litter capacity	Speed*	Quantity available
Ground ambulance	4	16 km/hr	10
Air ambulance	6	150 km/hr	2

* The speeds of the dedicated assets include the loading and unloading of patients[10].

Define variables:

$$\text{a/g ratio} = \frac{\textit{air ambulance speed}}{\textit{ground ambulance speed}} = \frac{150\ km/hr}{16\ km/hr} = 9.375\ ,$$

g capac = ground ambulance capacity,

a capac = air ambulance capacity,

g avail = number of ground ambulances available,

a avail = number of air ambulances available,

tot avail = the total number of ground and air ambulances available,

$$\text{g factor} = \frac{g\ avail}{tot\ avail} \times (g\ capac)\ ,$$

$$\text{a factor} = \frac{a\ avail}{tot\ avail} \times (a\ capac) \times (a/g\ ratio)\ ,$$

$$\text{Z factor} = \frac{maximum\ daily\ casualties}{g\ avail + a\ avail}\ ,$$

$$f_{k,ground} = \frac{(Z\ factor) \times (g\ factor)}{g\ capac}\ ,$$

$$f_{k,air} = \frac{(Z\ factor) \times (a\ factor)}{a\ capac}\ ,$$

The sum of the frequency of calls from all demand nodes within the theater ($f_{k,ground} + f_{k,air}$) will be used to calculate F_i, which will then lead to the calculations of the b_i's. By way of the Simplex Method, the PLSCP module determines that 3 ground ambulances and 1 air ambulance are required within M_1 (demand area 1), 4 ground ambulances and 1 air ambulance are required within M_2 (demand area 2), and 4 ground ambulances and 1 air ambulance are required within M_3 (demand area 3) as well (symbolically, for ground ambulances: $b_{1,ground} = 3$, $b_{2,ground} = 4$, $b_{3,ground} = 4$, and for air ambulances: $b_{1,air} = b_{2,air} = b_{3,air} = 1$).

Referring to Figure 1, the corresponding mathematical setup of the PLSCP, when solving for the optimal number of ground ambulances in the example scenario, is the following:

minimize $z = x_{11} + x_{21} + x_{31} + x_{41} + x_{51}$

subject to

$$\begin{array}{rcll} x_{11} + x_{21} & \geq & 3 & \text{(troop node 1 is within range of MTF 1 and 2)} \\ x_{21} + x_{31} + x_{41} + x_{51} & \geq & 4 & \text{(troop node 2 is within range of MTF 2, 3, 4, and 5)} \\ x_{41} + x_{51} & \geq & 4 & \text{(troop node 3 is within range of MTF 4 and 5)} \end{array}$$

where x_j are positive integers,

and when solving for the optimal number of air ambulances in the example scenario, the corresponding mathematical setup is the following:

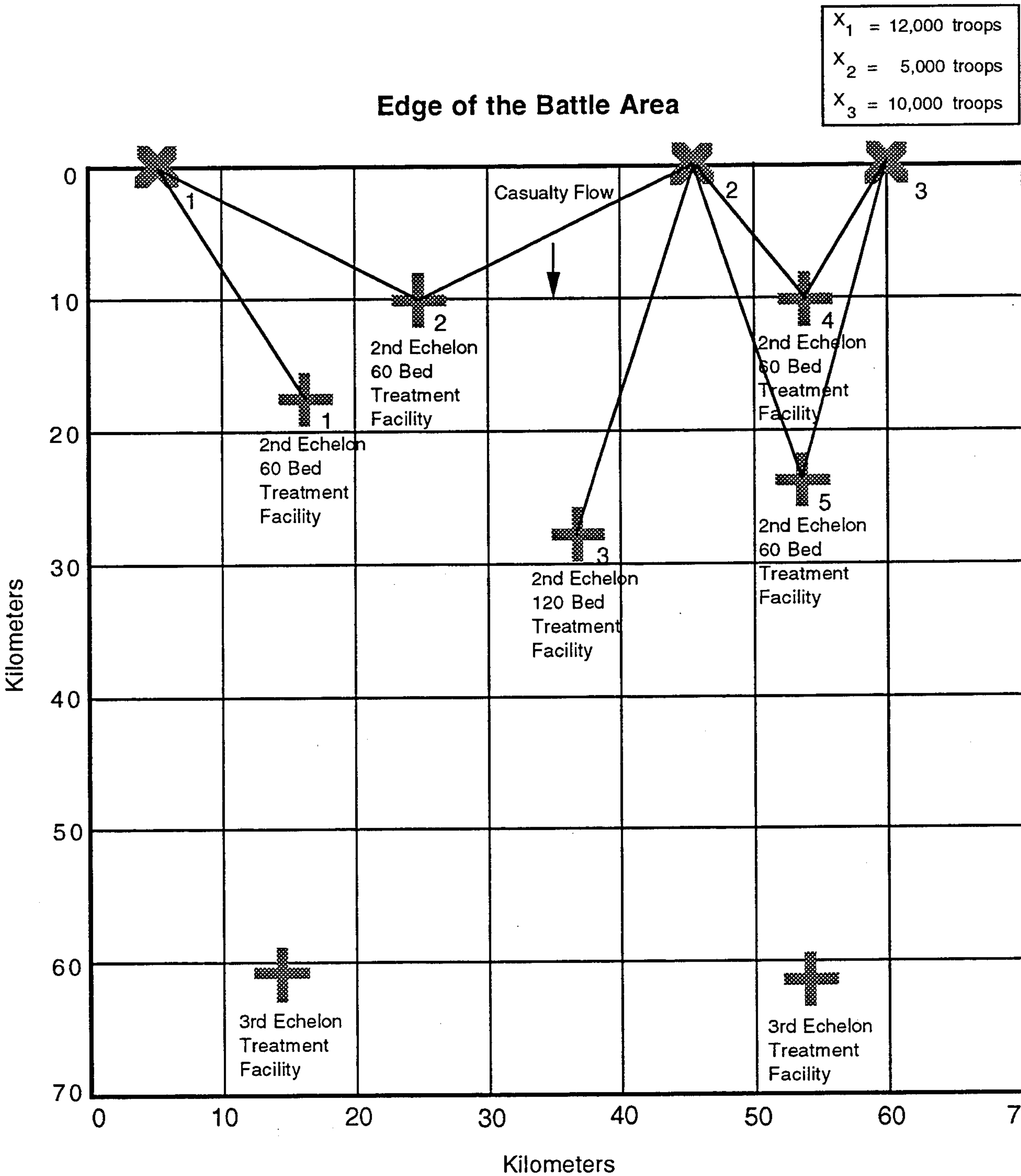

Figure 1. Sample input screen to the Optimization of Casualty Evacuation Assets (OPTEVAC) model showing troop deployment nodes (X's) and medical treatment facilities (+'s).

minimize $z = x_{12} + x_{22} + x_{32} + x_{42} + x_{52}$

subject to

$$x_{12} + x_{22} + x_{32} + x_{42} + x_{52} \geq 1 \quad \text{(troop node 1 is within range of each MTF)}$$
$$x_{12} + x_{22} + x_{32} + x_{42} + x_{52} \geq 1 \quad \text{(troop node 2 is within range of each MTF)}$$
$$x_{12} + x_{22} + x_{32} + x_{42} + x_{52} \geq 1 \quad \text{(troop node 3 is within range of each MTF)}$$

where x_j are positive integers.

In the aforementioned equations, the first subscript represents the Echelon II treatment facilities, and the second represents the type of vehicle. The first equation of the ground ambulance constraint matrix may be interpreted as "troop deployment node 1 is within range of medical treatment facilities 1 and 2 by way of ground ambulance". Similarly, each equation in the air ambulance constraint matrix indicates that none of the troop deployment nodes are out of air evacuation range for each of the five Echelon II treatment facilities.

After solving the above linear programming problems, the optimal solution was found to be placement of two ground ambulances at treatment facility 1, one at treatment facility 2, one at treatment facility 3, three at treatment facility 4, and one at treatment facility 5, for a total of eight necessary ground ambulances ($x_{11} = 2$, $x_{21} =1$, $x_{31} = 1$, $x_{41} = 3$, $x_{51} = 1$, and $z_{ground} = 8$). By inserting these results into the constraint matrix of the PLSCP for ground ambulances, it is clear that the results are indeed a minimum:

$$\begin{array}{lcl} 2 + 1 \geq 3 & & 3 \geq 3 \\ 1 + 1 + 3 + 1 \geq 4 & \Rightarrow & 6 \geq 4 \\ 3 + 1 \geq 4 & & 4 \geq 4 \end{array}$$

thus the constraint equations hold, and

$$z_{ground} = x_{11} + x_{21} + x_{31} + x_{41} + x_{51} = 2+1+1+3+1 = 8.$$

Further, only a single air ambulance was required ($z_{air} = 1$) and could be placed at any Echelon II facility, though placing it in the center facility would be the logical choice.

In this sample scenario, the optimization algorithms were able to minimize the number of evacuation assets required in the operation. Ten ground ambulances and two air ambulances were available for the operation, but only eight land transports and one air asset were necessary to perform the evacuation demands of the defined scenario. OPTEVAC finds the optimum numbers of required dedicated assets for a given theater of operations, and in the example scenario, the planner saved on resources by 20% for ground ambulances and 50% for air ambulances. These results demonstrate that the OPTEVAC model allows the user to determine the minimum numbers and optimal positioning of patient transportation assets required to meet the casualty handling demands of the operation.

Summary

The PLSCP model is the appropriate choice for modeling the efficient transport of casualties between intra-theater medical facilities. The model will be integrated into a software environment that will allow planners to project the optimal numbers and placement of assets needed for casualty handling in a theater of operations. The user will be able to input the dimensions of the theater, the quantity, types, and placement of medical treatment facilities, as well as the types of evacuation assets available. The OPTEVAC casualty evacuation model will then provide the optimal number and position of the needed ground and air ambulances.

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Christopher G. Blood, Serge A. Matheny

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Naval Health Research Center
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San Diego, CA 92186-5122

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Through the use of linear programming techniques, the optimal number and positioning of air and ground ambulances within a theater of operations may be determined to ensure the orderly transport of casualties from the front lines to third echelon medical treatment facilities. The Probabilistic Location Set Covering Problem has been chosen as the core module for a linear programming model to assist in these determinations. The Optimal Placement of Casualty Evacuation Assets (OPTEVAC) model prompts the user to enter the dimensions of the theater, troop deployment nodes, types of evacuation assets available, and preferred locations of medical treatment facilities. The OPTEVAC model then provides output as to the required numbers of air and ground ambulances as well as the optimal positioning of those evacuation assets and ambulance exchange points.

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